Volume 9, Issue 4, pp. 63-68, 2025.
International Journal of Scientific Engineering and Science
ISSN (Online): 2456-7361

A Mathematical Model for Predicting Performance of Pulverized Waste Rubber Tire as a Partial Replacement for Aggregate in the Production of Power Cable Trenches

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Abstract-*This study explores the integration of pulverized waste rubber tire (PWRT) as a partial replacement for traditional sand and cement in concrete, aimed at enhancing sustainability in construction. A Support Vector Machine (SVM) regression model was developed to predict compressive and flexural strengths, leveraging experimental data with varied PWRT replacement ratios. The research achieved optimal replacement values of 2.88% for cement and 3.82% for sand, yielding compressive and flexural strengths of 24.996 MPa and 3.0048 MPa, respectively. These results meet structural requirements while reducing reliance on natural aggregates and addressing environmental concerns tied to tire disposal. Performance metrics such as Mean Absolute Error (MAE) and Root Mean Square Error (RMSE) validated the model's reliability. This study underscores PWRT's potential as an eco-friendly substitute in concrete, offering a dual solution to material sustainability and waste management challenges, particularly for applications like power cable trenches where mechanical integrity is critical.*

Keywords: *Compressive strength, Flexural strength, Partial replacement of Sand, pulverized waste rubber tire, Support Vector Machine*

I. INTRODUCTION

A. Background Information

Concrete is one of the most used construction materials in the world due to its durability, adaptability, and strong compressive strength [10, 6, 4]. However, the manufacture of concrete is primarily reliant on natural aggregates and cement, both of which cause major environmental damage through resource exploitation and carbon emissions [2, 8]. On the other hand, the rapid increase in global tire production, driven by the growth of the automobile industry, has created significant challenges in the disposal of waste tires, especially as landfill space becomes increasingly limited [14]. In view of growing environmental concerns, researchers have looked into new materials that can partially replace traditional aggregates and lessen the environmental impact of concrete production.

Pulverized rubber tire waste (PWRT) is one alternative material that has gained popularity in recent years [12]. PWRT, made from end-of-life tires, provides an environmentally beneficial answer to the disposal issues caused by non-biodegradable garbage (see Fig. 1). Incorporating PWRT into concrete not only reduces the environmental impact of waste treatment, but it also allows the material's mechanical qualities to be adjusted for specialized uses, like power line tunnels. To ensure durability and resistance to external forces, these trenches require concrete with strong compressive and flexural strength. Fig. 1 shows the extent to which the disposal of waste tire rubber has become a critical global environmental issue, posing a serious threat to ecological sustainability. Incorporating scrap tire rubber into concrete as a partial substitute for natural aggregates is one possible way to manage it [13]. About 1 billion tires complete their lifespan each year, and by 2030, around 5 billion more are predicted to be thrown away every year [1]. Nonetheless, millions of these tires are stockpiled, disposed of in landfills, or buried, and only a tiny fraction is actually recycled. The increasing volume of polymeric wastes, such as tire rubber and polyethylene terephthalate (PET) bottles, further aggravates the problem.

Fig. 1: Tyre waste as environmental hazard when not disposed properly

B. Problem Statement

The conventional use of natural aggregates in concrete, while effective, is unsustainable due to resource depletion and the environmental impact of mining and processing [10, 6, 4, 2, 8, 5]. Despite the potential for PWRT to replace sand or cement, nothing is known about its impact on concrete's mechanical qualities. Furthermore, no thorough mathematical model exists to optimize the mix proportions of PWRT to achieve the requisite strength properties. This information gap impedes the implementation of sustainable construction approaches that make optimal use of waste resources.

C. Contribution

The development of a mathematical model for optimizing concrete mix designs that incorporate PWRT has two advantages: it promotes sustainability in construction and improves the mechanical performance of concrete for particular applications such as power line tunnels. The proposed model uses support vector machine (SVM) regression to effectively estimate compressive and flexural strengths, find suitable replacement ratios, and provide insight into the feasibility of adding PWRT into concrete. This study attempts to fill a knowledge gap by developing an SVM-based mathematical model and testing its performance on a dataset of concrete mixes with varied PWRT amounts.

D. Objective

To formulate a mathematical model using support vector machine (SVM) for predicting the compressive strength of concrete made with PWRT as a partial replacement for sand in the production of power cable trenches.

II. Related Works

A. Literature Review

The integration of PWRT as a partial replacement for sand in concrete has emerged as a promising approach for sustainable construction, particularly in addressing environmental concerns and reducing reliance on natural aggregates. The reviewed studies provide valuable insights into the mechanical and durability properties of rubberized concrete, which are crucial for developing predictive models using Support Vector Machines (SVM) to estimate compressive strength, particularly for specialized applications such as power cable trenches.

[12] conducted a comprehensive study on high-performance concrete (HPC) with 5%, 10%, and 15% replacement of natural sand with rubber particles, revealing a nonlinear relationship between rubber content and compressive strength. While strength reductions were negligible at 10% replacement, a marked decline was observed at 15%. These findings highlight the existence of an optimal replacement threshold, a key consideration when modeling strength predictions with SVM, which excels in capturing complex, nonlinear relationships.

Similarly [5] explored partial replacement of coarse aggregates with rubber tire waste in M25 grade concrete. The study found that replacement levels of 5% and 10% maintained acceptable compressive strength, while 15% resulted in significant reductions. The consistency of these results with [12] strengthens the argument for identifying threshold replacement levels, which could be incorporated into an SVM model as critical parameters for accurate predictions.

The durability properties of rubberized concrete also play a vital role in determining its compressive strength. [9] demonstrated that while higher rubber content (e.g., 7%) reduced compressive strength, it improved durability metrics such as water absorption and resistance to chloride penetration. Notably, a 3% rubber replacement produced the highest compressive strength (50.8 MPa), establishing it as the optimal level. These findings introduce another layer of complexity that could be addressed by SVM models, which can incorporate multiple performance metrics to predict strength while considering durability trade-offs.

The size and pre-treatment of rubber particles are also critical factors influencing concrete performance. [7] emphasized that rubber particles sized between 0–3 mm are optimal for durability. However, untreated rubber particles negatively impacted properties such as impermeability and carbonation resistance. Pre-treating rubber or incorporating supplementary cementitious materials (SCMs) was recommended as a strategy to mitigate these effects. These findings highlight the importance of including rubber particle size and pre-treatment variables in an SVM model to improve prediction accuracy.

[14] demonstrated that combining rubber with glass fibers (0.4% and 0.5% by weight of cement) mitigated strength reductions at higher rubber replacement levels. This approach suggests that multi-material combinations can optimize the performance of rubberized concrete. Sharma and Mehta [11] further investigated the use of silica fume as a mineral admixture to improve bonding properties, showing that despite reductions in strength with higher rubber content, combining rubber with SCMs can improve overall performance. These multi-material strategies are critical for SVM models, as they add variables that influence strength predictions.

B. Gaps in Research

While significant progress has been made in understanding the mechanical and durability properties of rubberized concrete, certain gaps remain. For instance, [13] highlighted the lack of extensive research on using rubber as a cementitious filler and the need to explore long-term durability, ductility, and energy absorption capacity. These gaps underline the need for advanced predictive tools like SVM to model complex interactions between multiple variables (e.g., replacement levels, rubber particle size, pre-treatment, and multi-material combinations) and predict compressive strength accurately.

The findings from these studies provide a strong foundation for developing a mathematical model using SVM to predict the compressive strength of concrete with PWRT as a partial sand replacement. SVM's ability to handle nonlinear relationships and multi-dimensional data makes it ideal for capturing the complex interactions between variables such as replacement percentage, particle size, pre-treatment methods, and admixture combinations. Additionally, SVM can incorporate durability metrics (e.g., water absorption and chloride penetration resistance) alongside strength parameters, making it a comprehensive tool for predicting performance in specialized applications like power cable trenches.

The reviewed works demonstrate that PWRT can be effectively used as a partial replacement for natural aggregates in concrete, but its impact on compressive strength and durability varies significantly based on replacement levels, particle size, and the use of supplementary materials. These complexities emphasize the need for predictive models like SVM to optimize concrete mix designs and ensure the performance of PWRT concrete in specific applications. Developing such models will contribute to sustainable construction practices while addressing the pressing issue of waste tire disposal.

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Volume 9, Issue 4, pp. 63-68, 2025. ISSN (Online): 2456-7361

III. Proposed Methodology

A. Batching

The methodology involved the use of ballast chips ($< 14mm$) as coarse aggregate in the experimental mix, assumed to be impurity-free and sourced from local Kenyan suppliers in Mihango, Utawala, Nairobi. The material batching follows the traditional concrete mix design for class 25 concrete, with a standard ratio of 1:1.5:3 (cement:sand:ballast) as per BS 8110-1:1985. However, the study modifies the sand proportion (1.5) by incorporating PWRT to identify an optimal mix design. These data obtained were normalized using (1)

$$x_{\text{norm}} = \frac{x - x_{\min}}{x_{\max} - x_{\min}} \quad (1)$$

This ensures that all input and target variables are scaled to a consistent range ($[0,1]$), which is crucial for machine learning models like Support Vector Machines (SVM). SVMs are sensitive to the scale of features, and normalization prevents certain features (e.g., percentages vs. strengths) from dominating the model due to differing magnitudes. This step also accelerates model convergence during training by reducing numerical instability.

SVM regression was used to model the relationship between the input variables (C, S) and the target variables $(f_{c'}, f_f)$. The model minimizes the following objective function:

$$\min_{w,b,\xi,\xi^*} \frac{1}{2} \parallel w \parallel^2 + C \sum_{i=1}^{n} (\xi_i + \xi_i^*) \quad (2)$$

Subject to:

$$\begin{aligned} &y_i - (w^T \phi(x_i) + b) \leq \epsilon + \xi_i \\ &(w^T \phi(x_i) + b) - y_i \leq \epsilon + \xi_i^*, \quad \xi_i, \xi_i^* \geq 0 \end{aligned} \quad (3)$$

SVM regression was chosen for its ability to handle non-linear relationships between input and output variables through the use of kernels. The Radial Basis Function (RBF) kernel

$$K(x_i, x_j) = \exp(-\gamma \parallel x_i - x_j \parallel^2) \quad (4)$$

was employed because it can map the input data to a higher-dimensional space, allowing the model to capture complex, non-linear interactions between C, S and the strengths $(f_{c'}, f_f)$. The regularization parameter C balances model complexity and prediction error, ensuring that the model generalizes well to unseen data. The choice of SVM regression was particularly motivated by its robustness to overfitting, especially for small-to-medium-sized datasets. To solve the SVM optimization problem, the Lagrangian function is introduced as follows

$$\mathcal{L}(w, b, \xi, \xi^*, \lambda, \alpha, \alpha^*) = \frac{1}{2} \parallel w \parallel^2 + C \sum_{i=1}^{n} (\xi_i + \xi_i^*) - \sum_{i=1}^{n} \lambda_i (\xi_i + \xi_i^*) - \sum_{i=1}^{n} \alpha_i [y_i - (w^T \phi(x_i) + b) - \epsilon - \xi_i] - \sum_{i=1}^{n} \alpha_i^* [(w^T \phi(x_i) + b) - y_i - \epsilon - \xi_i^*] \quad (5)$$

The Lagrangian function incorporates both the objective function and the constraints of the SVM problem. By minimizing the Lagrangian with respect to primal variables (w, b, ξ, ξ^*) and maximizing with respect to dual variables $(\lambda, \alpha, \alpha^*)$, the optimization problem was reformulated as a dual problem that is computationally efficient to solve. This approach enables the SVM to handle high-dimensional feature spaces introduced by the kernel function.

B. Performance Evaluation

The model predictions ($\hat{y}$) were compared with actual values (y) using the following metrics:

1. Mean Absolute Error (MAE):

$$\text{MAE} = \frac{1}{n} \sum_{i=1}^{n} |y_i - \hat{y}_i| \quad (6)$$

2. Mean Squared Error (MSE):

$$\text{MSE} = \frac{1}{n} \sum_{i=1}^{n} (y_i - \hat{y}_i)^2 \quad (7)$$

3. Root Mean Squared Error (RMSE):

$$\text{RMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (y_i - \hat{y}_i)^2} \quad (8)$$

These metrics are widely used to evaluate regression models [3]. MAE provides the average absolute deviation between predictions and actual values, emphasizing individual errors equally. MSE penalizes larger errors more heavily due to squaring, making it sensitive to outliers. RMSE is the square root of MSE, providing an interpretable measure of prediction error in the same units as the target variables. These metrics comprehensively evaluate the accuracy and consistency of the SVM model.

C. Optimization of Replacement Ratios

The optimization objective was to maximize the combined strengths $(f_{c'}, f_f)$ while satisfying the constraints:

$$f_{c'}(C, S) \leq 25 \text{ MPa}, \quad f_f(C, S) \leq 3.5 \text{ MPa} \quad (9)$$

$$\max_{C,S} \left[f_{c'}(C, S) + f_f(C, S) \right] \quad (10)$$

The optimization problem ensures that the predicted strengths meet structural requirements for compressive and flexural strength. The MATLAB fmincon function was used because it efficiently handles constrained optimization problems, allowing the solution to adhere to the strength limits while finding the optimal replacement ratios (C_{opt}, S_{opt}).

D. Denormalization and Final Results

The predicted strengths at the optimal ratios were denormalized back to their original scale using:

$$y = y_{\text{norm}} \cdot (y_{\max} - y_{\min}) + y_{\min} \quad (11)$$

Denormalization was necessary to interpret the results in terms of the original strength values. It allows the optimized concrete mix proportions to be directly applied in practical applications, ensuring the findings are usable in real-world scenarios.

IV. Results

A. Experimental Data

TABLE I summarize the parameters used in the experimental setup via R2023b.

TABLE I. Key variables and parameters summary

Symbol	Description	Value (if applicable)
C	Cement replacement ratio (%)	0–7%
S	Sand replacement ratio (%)	0–11%
$f_{c'}$	Compressive strength (MPa)	10–25 MPa
f_f	Flexural strength (MPa)	1.5–3 MPa
w	SVM weight vector	Computed by model
b	SVM bias term	Computed by model
ϵ	Insensitive loss margin	0.1
C (SVM)	Regularization parameter	10
γ	RBF kernel scale parameter	Automatic (auto)

B. Data

The data were attained in two batches, the preliminary results and the optimal results. In this paper, we used the

International Journal of Scientific Engineering and Science
Volume 9, Issue 4, pp. 63-68, 2025. ISSN (Online): 2456-7361

optimal results presented in TABLE II.

TABLE II. Summary of Experimental Results for determination of Optimal Control

Batch Mark	% replacement		Strength (MPa)	
	Cement	Sand	Compressive	Flexural
OP1	3%	10%	10.64	1.94
OP2	2%	3%	19.94	2.66
OP3	7%	3%	24.99	2.97
OP4	5%	3%	22.35	2.81
OP5	4%	3%	24.03	2.92
OP6	3.5%	3%	24.39	2.94
OP7	4.5%	3%	24.83	2.96
OP8	4.25%	3%	22.53	2.82
OP9	4.25%	3.5%	16.35	2.40
OP10	4.5%	3.5%	17.00	2.45
OP11	4.5%	3.75%	18.11	2.53
OP12	4.5%	5%	15.81	2.36
OP13	2%	2.5%	18.29	2.54
OP14	2%	3.5%	20.89	2.72
OP15	2%	4%	14.01	2.23
OP16	2%	4.5%	21.69	2.77
OP17	2.5%	3.5%	20.89	2.72
OP18	2.5%	4.25%	24.35	2.93
OP19	2.5%	3.75%	21.79	2.78
OP20	2%	5%	17.56	2.49
OP21	2%	11%	10.31	1.91
OP22	2.5%	5%	6.83	1.55
OP23	2.5%	11%	8.08	1.68

Table 2 indicate that the dataset contains C : Cement replacement ratio (%) (ranging from 0% to 7%); S: Sand replacement ratio (%) (ranging from 0% to 11%); f_c, : Compressive strength (MPa) (ranging from 10 MPa to 25 MPa); and f_f: Flexural strength (MPa) (ranging from 1.5 MPa to 3 MPa).

C. Simulation Results

Fig. 2 summarize the optimal results.

```
--- Optimization Results ---
Optimal Cement Replacement (C): 2.8785%
Optimal Sand Replacement (S): 3.8229%
Final Mix Ratio (C:C(R):S:S(R):B): 1:0.0003:1.5:0.0004:3
Optimal Compressive Strength: 24.9960 MPa
Optimal Flexural Strength: 3.0048 MPa
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Fig. 2: Extract of optimal results

The optimization results in Fig. 2 demonstrate the ability of the model to identify optimal replacement ratios for cement and sand to achieve high compressive and flexural strengths while adhering to predefined constraints. The optimal cement replacement ratio is 2.8785%, while the optimal sand replacement ratio is 3.8229%. These values indicate that a small percentage of pulverized rubber as a replacement for cement and sand is sufficient to maximize the mechanical properties of the concrete mix. The final mix ratio is expressed as

$C: C(R): S: S(R): B =$
$1: 0.0003: 1.5: 0.0004: 3C: C(R): S: S(R): B =$
$1: 0.0003: 1.5: 0.0004: 3.$

where CC is cement, C(R) is the cement replacement (rubber), SS is sand, S(R) is the sand replacement (rubber), and BB is ballast (aggregates). This mix ratio incorporates the optimal replacement values and ensures a balanced composition of all material components. The small proportion of pulverized rubber in the replacement mix underscores its effectiveness in achieving the desired properties without significantly altering the original concrete mix design. The predicted optimal compressive strength is 24.9960 MPa, and the predicted optimal flexural strength is 3.0048 MPa. Both values are close to the upper constraints of 25 MPa for compressive strength and 3.5 MPa for flexural strength. This demonstrates that the optimized replacement ratios effectively balance mechanical properties, achieving high performance while staying within acceptable limits.

The findings demonstrate that pulverized rubber is a viable alternative material for partial replacement. Even with minimal replacement percentages, the optimized mix achieves high compressive and flexural strengths, making pulverized rubber a sustainable and efficient solution. The compressive strength of 24.9960 MPa indicates that the mix meets structural requirements, as it is close to the maximum allowable limit. The mix's capacity to withstand bending and tensile stresses, which are essential for structural uses like power cable trenches, is likewise validated by a flexural strength of 3.0048 MPa. In addition to strength performance, the incorporation of pulverized rubber contributes to sustainability by reducing the reliance on traditional materials like cement and sand. This environmentally friendly approach supports sustainable construction practices without compromising mechanical performance. The performance of the model was also tested using MAE (6), MSE (7) and RMSE (8) and the results are presented in Fig. 3.

```
--- Model Performance ---
Compressive Strength:
MAE: 1.6927 MPa, MSE: 3.3839 MPa^2, RMSE: 1.8395 MPa
Flexural Strength:
MAE: 0.1284 MPa, MSE: 0.0184 MPa^2, RMSE: 0.1358 MPa
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Fig. 3: Extract of performance of model

The performance results evaluate the accuracy of the SVM regression model for predicting compressive and flexural strengths using the metrics MAE, MSE, and RMSE. These metrics quantify the difference between the model's predictions and the actual values, providing insight into its reliability. In Fig. 3, compressive strength indicate that the model achieves an MAE of 1.6927 MPa, indicating that, on average, the predictions deviate from the true values by approximately 1.69 MPa. Considering that the compressive strength values in the dataset range from 10 MPa to 25 MPa, this represents a moderate error, which is acceptable for practical applications. The MSE, measuring the average of squared differences between predictions and actual values, is 3.3839 MPa², reflecting the model's sensitivity to larger deviations. The RMSE, at 1.8395 MPa shows that the predictions typically deviate by 1.84 MPa from the actual values. While the errors for compressive strength are slightly higher, they remain within reasonable limits for practical use, suggesting that the model

International Journal of Scientific Engineering and Science
Volume 9, Issue 4, pp. 63-68, 2025. ISSN (Online): 2456-7361

captures the underlying patterns in the data effectively, albeit with room for improvement.

For flexural strength, the model performs exceptionally well, achieving an MAE of 0.1284 MPa. This indicates that the average deviation between predictions and actual values is only 0.128 MPa, which is very small compared to the dataset's range of flexural strengths (1.5 MPa to 3 MPa). The MSE is similarly low, at 0.0184 MPa², indicating minimal large prediction errors. The RMSE of 0.1358 MPa further confirms the model's precision, showing that the typical deviation of predictions from the true values is less than 0.14 MPa. These results highlight the model's strong ability to predict flexural strength with high accuracy and consistency. Comparing the two predictions, the model performs better for flexural strength than for compressive strength. The errors for flexural strength are significantly lower across all metrics, likely due to the relatively consistent and less variable nature of flexural strength data compared to compressive strength. Compressive strength predictions show slightly higher errors, which may stem from greater variability in the data or the inherent complexity of the relationship between input features and compressive strength. The model demonstrates reliable performance for both compressive and flexural strength predictions. While the predictions for compressive strength could be further improved by refining the model or expanding the dataset, the results are still acceptable for practical engineering applications. On the other hand, the model's performance for flexural strength is excellent, ensuring precise and reliable predictions. These findings underline the suitability of the SVM regression model for optimizing concrete mix designs, particularly in scenarios where both compressive and flexural strengths are critical. The optimal results is also compared the laboratory results and is presented in Fig. 4 and Fig. 5.

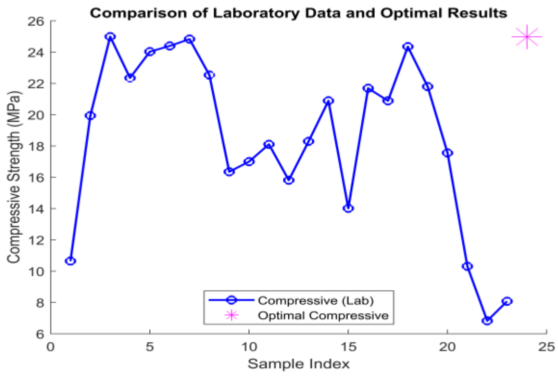

Fig. 4: Comparison of laboratory compressive strength and predicted

Fig. 4 indicate that the laboratory compressive strength values range from approximately 10 MPa to 25 MPa, showing significant variability across the samples. Peaks and troughs are evident, corresponding to different cement and sand replacement ratios tested in the laboratory. The optimal compressive strength, represented by the magenta star, lies near the upper range of the laboratory data, indicating that the selected replacement ratios result in a mix with high compressive strength. This result demonstrates that the optimized mix design, incorporating pulverized rubber as a partial replacement for cement and sand, achieves compressive strengths comparable to or exceeding the majority of the laboratory samples. The result highlights the success of the optimization model in selecting ratios that balance material composition while ensuring structural integrity.

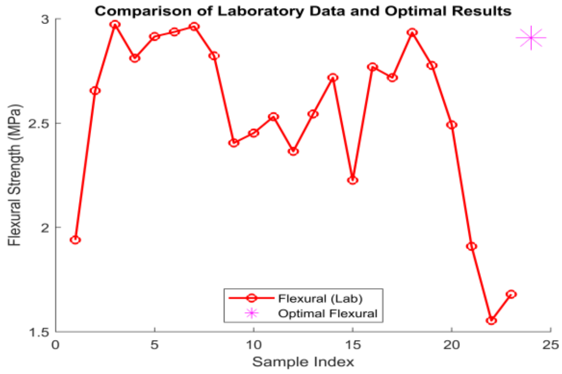

Fig. 5: Comparison of laboratory flexural strength and predicted.

Fig. 5 ndicate that the flexural strength values vary between 1.5 MPa and 3 MPa, with some samples exhibiting lower performance. The optimal flexural strength, represented by the magenta star, aligns closely with the upper range of the laboratory data. This result indicates that the optimized replacement ratios maintain or improve flexural strength while incorporating pulverized rubber into the mix. Flexural strength is critical in applications where tensile or bending forces are significant. The results demonstrate that the optimized mix design not only supports compressive strength but also ensures adequate flexural properties, making it suitable for structural applications such as power cable trenches. The predicted optimal compressive and flexural strengths reflect the effectiveness of using pulverized rubber as a partial replacement for cement and sand. These optimized strengths align with or surpass the laboratory results, highlighting the benefits of the optimization process. The optimized mix design achieves high compressive and flexural strengths, meeting performance requirements for structural applications. Pulverized rubber provides an eco-friendly and cost-effective alternative to traditional materials, contributing to sustainable construction practices. The results demonstrate the importance of carefully selecting replacement ratios to balance mechanical properties and maximize performance. These findings validate the feasibility of using pulverized rubber in concrete applications, particularly where both compressive and flexural strength are essential. The analysis demonstrates the potential for deploying such optimized mixes in real-world applications, such as power cable trenches, where durability and structural integrity are crucial.

V. Conclusion

This study shows that using pulverized waste rubber tires (PWRT) as a partial substitute for natural aggregates in concrete is both practical and advantageous. By employing Support Vector Machine (SVM) regression modeling, the study provides an optimized mix design that balances mechanical properties with sustainability goals. The optimal replacement ratios, 2.88% for cement and 3.82% for sand—achieve compressive and flexural strengths of 24.996 MPa and 3.0048 MPa, respectively, meeting the structural demands of applications like power cable trenches. The model's strong performance, reflected in metrics such as MAE and RMSE, highlights its predictive accuracy and robustness, particularly for flexural strength.

The findings indicate that even small proportions of PWRT can significantly enhance the environmental and mechanical performance of concrete. This approach addresses critical issues such as the ecological impact of traditional aggregates and the growing problem of waste tire disposal. The study also highlights the importance of advanced modeling techniques like SVM in optimizing complex material interactions and achieving desired performance levels. By providing a practical, scalable solution for sustainable construction, this work bridges a significant gap in material science research. The successful integration of PWRT not only mitigates waste management challenges but also promotes a shift towards greener construction practices without compromising durability or strength. These contributions align with global sustainability goals, paving the way for innovative applications of waste-derived materials in the construction industry.

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